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Description

SYSTEM AND METHOD FOR JOINT MAXIMAL RATIO COMBINING USING TIME-DOMAIN BASED SIGNAL PROCESSING

BACKGROUND OF INVENTION

[0001] This application is a continuation of U.S. Application No. 10/064,482 filed July 18, 2002, pending, which in turn claims priority to U.S. Provisional Application No. 60/361,055, filed March 1, 2002, and to U.S. Provisional Application No. 60/380,139, filed May 6, 2002. The entirety of each of these prior applications is incorporated herein by reference.

[0002] RELATED APPLICATIONS

[0003] This application is related to commonly assigned and co-pending U.S. Non-Provisional Application No. 10/174,728 filed June 19, 2002 and entitled "SYSTEM AND METHOD FOR ANTENNA DIVERSITY USING JOINT MAXIMAL RATIO

COMBINING" and to commonly assigned and co-pending U.S. Non-Provisional Application No. 10/174,689 filed June 19, 2002, and entitled "SYSTEM AND METHOD FOR ANTENNA DIVERSITY USING EQUAL POWER GAIN JOINT MAXIMAL RATIO COMBINING."

[0004] The present invention is directed to a joint temporal and spatial antenna processing scheme useful in wireless communication applications, such as short-range wireless applications.

[0005] Antenna diversity schemes are well known techniques to improve the performance of radio frequency (RF) communication between two RF devices. Types of antenna diversity schemes include antenna selection diversity and maximal ratio combining. In an antenna selection diversity scheme, a radio communication device selects one of N (e.g., two) antennas for transmission to a particular communication device based on which of its N antennas best received a signal from that radio communication device. On the other hand, maximal ratio combining schemes involve scaling the signal to be transmitted with a complex antenna weight associated with a corresponding one of a plurality of antennas. A signal received by a plurality of antennas can also be weighted by a plurality of complex

receive antenna weights. Selection of the antenna weights to optimize communication between two communication devices determines the performance of maximal ratio combining schemes.

[0006] A joint maximal ratio combining antenna processing technique is one in which a first communication device, having a plurality of antennas, weights a signal to be transmitted by its antennas to a second communication device also having a plurality of antennas. The second communication device weights and combines the received signals received by its antennas. The transmit weights and receive weights are determined to optimize the link margin, e.g., optimize the signal-to-noise ratio of signals received by one device from the other. Techniques related to joint maximal ratio combining, also called composite beamforming (CBF), are the subject matter of above-identified commonly assigned co-pending application. These techniques significantly extend the range of communication between the two communication devices.

[0007] An approach is desired for a joint maximal ratio combining technique that requires relatively low complexity computations be performed in a communication device.

SUMMARY OF INVENTION

[0008] A spatial signal processing system and method are provided to optimize the received signal-to-noise ratio (SNR) at a radio communication device based on the transmit filter at another radio communication device. An iterative process is provided to determine complex weights for tapped delay-line transmit filters at each of two communication devices that optimize the received SNR. When one communication device receives a signal from another device, it generates a receive filter matrix from a signal received by its one or more antennas. The receive filter matrix is comprised of one or more sub-matrices each being a convolution matrix derived from a receive filter sub-vector, wherein each receive filter sub-vector defines one or more complex weights associated with a receive tapped-delay line filter for the one or more antennas. The receiving device computes the eigenvector corresponding to the maximum eigenvalue of a product of the receive filter matrix and a Hermitian of the receive filter matrix. This eigenvector is the principal eigenvector of that matrix multiplication product. The principal eigenvector is comprised of one or more sub-vectors each having a length corresponding to a number of taps of a transmit tapped-delay line filter associated with the one or more antennas.

From the one or more sub-vectors of the principal eigenvector one or more transmit filter sub-vectors that form a transmit filter vector are determined. Each transmit filter sub-vector corresponds to the one or more antennas of the second communication device and defining one or more complex weights associated with the transmit tapped-delay line filter for the one or more antennas of the second communication device. The transmit filter vector is used by that device when transmitting a signal back to the other device.

[0009] The two communication devices will ultimately converge to transmit filter vectors that optimize the received SNR at the output of the receive filters of the other device. The range of communication, i.e., distance between the devices, is significantly increased using the techniques described herein.

[0010] The above and other objects and advantages will become more readily apparent when reference is made to the following description taken in conjunction with the accompanying drawings.

Brief Description of Drawings

[0011] FIG. 1 is a block diagram of two communication devices performing time-domain based composite beamforming.

[0012] FIG. 2 is a diagram showing an exemplary channel matrix.

[0013] FIG. 3 is a diagram showing exemplary transmit filter vectors.

[0014] FIG. 4 is a flow diagram illustrating an iterative process for time-domain based composite beamforming between two communication devices.

[0015] FIG. 5 is a graphical diagram showing exemplary results of the time-domain based iterative process.

[0016] FIG. 6 is a graphical diagram showing performance loss for ideal channel conditions.

[0017] FIG. 7 is a graphical diagram showing performance loss for the iterative process.

[0018] FIG. 8 is a block diagram of a communication device suitable for implementing the time-domain composite beamforming signal processing.

DETAILED DESCRIPTION

[0019] Referring first to FIG. 1, two radio communication devices 100 and 200 are shown that communicate with each other across a wireless transmission channel that can be defined by a channel matrix H (or H^T, where ^{T} denotes the transpose operator). When the signal-to-noise ratio (SNR) at the output of the receive filters of one device is optimized

with respect to the transmit filters at the other device, the ideal transmit filter vector w_T is given by the eigenvector corresponding to the maximum eigenvalue e_{max} of $(H^H H)$, which is the principal eigenvector of $(H^H H)$, where ^{H} denotes the Hermitian operator. This ideal case assumes that the devices have direct knowledge of the channel, obtained from training sequences or from a separate signal containing channel information that is transmitted from one device to the other.

[0020] In the drawings, vectors are underlined (and italicized) and matrices are capitalized and bolded (and italicized), whereas in the text, these quantities are in most cases indicated as either a vector or a matrix.

[0021] Described below is a system and method to optimize the SNR at the output of the receive filters of one device (hereinafter referred to as the received SNR) with respect to tapped delay-line transmit filters at another device without direct knowledge of the channel between the devices. Using an estimate of the channel obtained from a signal received at one device from another device, an iterative process is provided that determines the transmit filters at the communication device at each iteration. The transmit filters at each device converge to a received SNR

that is within 1-2dB of the ideal case SNR in about 2 to 3 iterations for more than 90% of channel realizations.

[0022] With this background, communication device 100 includes, among other components, a transmit shaping filter 110, a plurality of transmit antenna filters 120(1)-120(N) and N plurality of antennas 130(1) to 130(N). There is a transmit antenna filter 120(i) associated with a corresponding antenna 130(i), where i is the antenna index, for i = 1 to N. Each transmit antenna filter 120(i) is, for example, a tapped delay-line filter having a number of taps. For each tap of the tapped delay-line filter, there is a complex weight having a magnitude component and a phase component. For example, a single tap delay-line filter has a single weight, and therefore a flat or constant magnitude and a flat or constant phase response across frequency. The characteristic of each transmit filter 120 is defined by a transmit filter sub-vector $w^{i}_{T,D1}$, and the length of the transmit filter sub-vector corresponds to the number of taps of the transmit antenna filter 120(i). The entry in each sub-vector defines the corresponding tap weight for the delay-line filter. The transmit filter sub-vectors can be grouped together to form a transmit filter vector. The filter vector and sub-vectors will be described

further hereinafter.

[0023] Similarly, for purposes of processing a received signal, the communication device 100 comprises a plurality of receive antenna filters 140(1) to 140(N) and a combiner/detector 150. There is a receive antenna filter 140(i) coupled to an associated antenna 130(i). Each receive antenna filter 140(i) is, for example, a tapped delay-line filter having a number of taps, and is essentially a matched filter. A combiner/equalizer 150 is coupled to the receive antenna filters 140(1) to 140(N). The characteristic of each receive filter 140(i) is defined by a receive filter sub-vector $w^{i}_{R,D1}$ having a length corresponding to the number of taps of the receive antenna filters 140. The entry in each receive filter sub-vector $w^{i}_{R,D1}$ defines the corresponding complex tap weight for the delay-line filter. There are computation elements or blocks represented by reference numeral 160 in communication device 100 that perform discrete signal computations with respect to the transmit antenna filters 120 and receive antenna filters 140 described hereinafter.

[0024] Communication device 200 includes components similar to those in communication device 100. Communication device includes M plurality of antennas 210(1) to 210(M),

a plurality of receive antenna filters 220(1) to 220(M) and a combiner/equalizer 230. There is a receive antenna filter 220(j) (i.e., a matched filter) associated with a corresponding antenna 210(j), where j is the antenna index for j = 1 to M. The characteristic of each receive antenna filter 220(j) is defined by a receive filter sub-vector $w^{j}_{R,D2}$. The receive filter sub-vectors can be grouped together to form a receive filter vector. On the transmit side, there is a transmit shaping filter 240 and a plurality of transmit antenna filters 250(1) to 250(M) each associated with a corresponding one of the antennas 210(1) to 210(M). The characteristic of each transmit antenna filter 250(j) is defined by a transmit filter sub-vector $w^{j}_{T,D2}$. Like communication device 100, the receive antenna filters 220(j) and the transmit antenna filters 250(j) are, for example, tapped delay-line filters of a number of taps. The length of the receive filter sub-vectors $w^{j}_{R,D2}$ correspond to the number of taps of the receive antenna filters 220(j), and the length of the transmit filter sub-vectors $w^{j}_{T,D2}$ correspond to the number of taps of the transmit antenna filters 250(j). Communication device 200 has computation elements or blocks represented by reference numeral 260 that perform discrete signal computations with respect to

the transmit antenna filters 250(j) and receive antenna filters 220(j) described hereinafter. While FIG. 1 shows that communication devices 100 and 200 each have a plurality of antennas, it should be understood that one of them, for example, communication device 200, may have a single antenna (and therefore a single transmit antenna filter and a single receive antenna filter). In this case, only one of the two devices of the communication link adapts its transmit filter to optimize the receive SNR at the device with the single antenna. The device with multiple antennas will adapt its receive filter to optimize its receive SNR from the device with a single antenna.

[0025] The communication device block diagram shown in FIG. 1 is useful in a transceiver that processes signals of any wireless communication modulation standard or format. Likewise, the methods described herein are applicable to any wireless communication modulation standard or format. An example is a code division multiple access (CDMA) format using a single carrier. A more specific example is the single-carrier scheme of the IEEE 802.11b short-range wireless standard.

[0026] It should be understood to those of skill in the art that FIG. 1 is a simplification of a communication device archi-

tecture to highlight those components relevant to the composite beamforming techniques described herein. For example, FIG. 1 omits (for the sake of conciseness) digital-to-analog converters and a radio frequency (RF) section between the antennas and the antenna filters. FIG. 8, described hereinafter, is an example of a more complete exemplary block diagram of a communication device. The components shown in FIG. 1 are elements that typically are included in a baseband section of a communication device and may be implemented by discrete elements or by field programmable gate arrays for digital signal processing integrated circuit implementations. The combiner/equalizer 150 (and 230) is meant to represent any suitable signal processing components used in a receiver. For example, in the case of a decision feedback equalizer (DFE), the combiner/equalizer block includes feedforward filters, a decision block and a feedback filter. In the case of a maximum likelihood sequence estimator (MLSE) receiver, there is a MLSE in the combiner/equalizer block 150 (and 230), and in the case of a direct sequence spread spectrum (DSSS) receiver, there is a correlator in the combiner/equalizer block 150 (and 230).

[0027] When communication device 100 transmits a signal to

communication device 200, the communication channel between the N plurality of antennas 130(1) to 130(N) and the M plurality of antennas 210(1) to 210(M) is defined by a channel matrix H of appropriate dimension as is shown in FIG. 2, described hereinafter. Similarly, when communication device 200 transmits a signal to communication device 100, the communication channel between the M plurality of antennas 210(1) to 210(M) and the N plurality of antennas 130(1) to 130(N) is defined by a channel matrix H^T.

[0028] Turning to FIG. 2, the channel matrix H is described in further detail. The channel response from an antenna i of communication device 100 to an antenna j of communication device 200 is defined by a channel response vector h^{ij} and can be modeled as a tapped delay-line filter having a length or number of taps L. The channel response vector h^{ij} can be written as shown in FIG. 2. The channel response vector can also be written as a convolution matrix H_{ij}, where i is the index for the N plurality of antennas of communication device 100 and j is the index for the M plurality of antennas of communication device 200. The dimensions of the channel response matrix H_{ij} is (L + LTD1 - 1) x LTD1, where LTD1 is the length of the trans-

mit filters of the first communication device 100.

[0029] Referring back to FIG. 1, the transmit antenna filters 120(i) in communication device 100 have a length (i.e., number of taps), and the transmit antenna filters 250(j) in communication device 200 have a length. The lengths of the transmit antenna filters 120(i) and 250(j) are not necessarily the same, and are chosen according to implementation/performance requirements. Obviously, the more taps a filter has, the greater performance it will have, at the expense of implementation cost and complexity. The length of the receive antenna filters 140(i) in communication device 100 depends on the length of the transmit antenna filters 250(j) and the length of the channel response vectorh^{ij} suitable for modeling the channel response between the first and second communication devices. It can be shown that the length of the receive antenna filters 140(i) (when receiving a signal from communication device 200) is equal to the sum of the length of the transmit antenna filters 250(j) plus the length of the channel response vector h^{ij}. Similarly, the length of the receive antenna filters 220(j) (when receiving a signal from communication device 100) is equal to the sum of the length of the transmit antenna filters 120(i) plus the length of the

channel response vector h^{ij}. The length of the transmit antenna filters 120(i) and 250(j) do not depend on the length of the receive antenna filters 140(i) and 220(j), respectively, and can be set to any desired length. For example, it has been determined through simulation that transmit antenna filters 120(i) and 250(j) can be single tap delay-line filters and still achieve acceptable performance.

[0030] With reference to FIG. 3, similar to the channel matrix H, there is a transmit filter matrix $W^{i}_{T,D1}$ associated with each antenna i of the first communication device 100 (for transmitting a signal to the second communication device 200). A transmit filter super matrix is matrix comprising a plurality of sub-matrices corresponding to the transmit filter matrix associated with each antenna i. The transmit filter matrix $W^{i}_{T,D1}$ is a convolution matrix representation of the corresponding transmit antenna filter sub-vector $w^{i}_{T,D1}$. The transmit antenna filter vector $w_{T,D1}$ is essentially a super-vector comprised of a plurality of transmit filter sub-vectors $w^{i}_{T,D1}$, each transmit filter sub-vector corresponding to or associated with a transmit filter (FIG. 1), which in turn is associated with one of the plurality of antennas of the first communication device 100. For notation purposes, the length of each transmit filter sub-

vector of communication device 100 is LTD1, as described above in conjunction with FIG. 2. Therefore, the length of the transmit antenna filter vector is N * LTD1. The dimensions of each transmit filter matrix is (LTD1 + L - 1) x L, and the dimension of each transmit filter sub-vector is LTD1 x 1.

[0031] Though not shown in FIG. 3, the transmit filter vector of the second communication device 200 (for transmitting a signal to the first communication device 100) is similarly defined as $w^{j}_{T,D2}$, associated with each antenna j of the second communication device 200. The length of the transmit antenna filter sub-vector (and thus the number of taps of the transmit antenna filters 250(j)) for the second communication device 200 is denoted LTD2. The receive filter matrix for the first communication device is denoted $W_{R,D1}$, and the receive filter matrix for the second communication device is denoted $W_{R,D2}$. Each receive filter matrix comprises a sub-matrix for each antenna of that device. Each sub-matrix is a convolution matrix derived from the receive filter sub-vector associated with the corresponding antenna depicted in FIG. 3. The filter length LTD1 of the first communication device and the filter length of LTD2 of the second communication device

need not be the same.

[0032] FIG. 4 illustrates the iterative process 400. The process 400 is described with respect to communication between the first communication device (denoted by the index D1) having N antennas and the second communication device (denoted by the index D2) having M antennas. It is to be understood that the process is applicable to any wireless communication application, such as, for example, a short-range wireless application. The process begins in step 410 when the first communication device transmits a signal to the second communication device using an initial transmit filter vector $w_{T,D1,0} = [10\ldots0,10\ldots0,10\ldots0,10\ldots0]^T$ according to the notation shown, normalized by the factor $1/(N)^{½}$ (1 divided by the square root of N), where N is the number of antennas of the first communication device. The purpose of this factor will be described hereinafter. The initial transmit filter vector has a unity value at the initial position in each sub-vector for each antenna. In step 410, the first communication device transmits a signal with the initial transmit filter vector to the second communication device. The second communication device receives the transmitted signal, and from the received signal, the second communication device estimates a vector

corresponding to the product $W_{R,D2,0} e_0$, where e_0 is the vector $[10 \ldots 0]^T$. From this quantity, the second communication device obtains the initial receive filter vector $w_{R,D2,0}$ and builds the receive filter matrix $W_{R,D2,0}$ with dimensions that, after further computations, will result in a transmit filter vector $w_{T,D2}$ that has the desired filter length.

[0033] In step 420, the second communication device computes a principal eigenvector $u_{T,D2}$ which is the eigenvector corresponding to the maximum eigenvalue of the product of $\{(W_{R,D2,0})^H W_{R,D2,0}\}$. The principal eigenvector $u_{T,D2,0}$ has a length of M * LTD2. The principal eigenvector $u_{T,D2,0}$ is a super vector, or vector of sub-vectors, where each sub-vector $u^j_{T,D2,0}$ has a length LTD2 and is used to derive the transmit antenna filter sub-vector $w^j_{T,D2,0}$ for a corresponding antenna of the second communication device.

[0034] Each transmit filter sub-vector $w^j_{T,D2}$ can take on one of two values as shown in FIG. 4. In one case, the transmit filter sub-vector $w^j_{T,D2}$ is equal to the corresponding sub-vector $u^j_{T,D2,0}$ of the principal eigenvector $u_{T,D20}$. This is called the non-equal gain case indicated "NON-EG" in FIG. 4. In another case, the transmit antenna sub-vector $w^j_{T,D2}$ is equal to the corresponding sub-vector $u^j_{T,D2,0}$

of the principal eigenvector $u_{T,D2,0}$ divided by the norm of that sub-vector $u^{j}_{T,D2,0}$ and by $(M)^{½}$ (square root of M). This case is called the equal-gain case, indicated "EG" in FIG. 4. This further computation equal-gain normalizes the magnitude of each filter sub-vector so that the power of the signal transmitted at each antenna using the transmit filter sub-vectors is equal. This equal gain constraint is advantageous because it has been found to yield performance very close to non-equal gain antenna processing (within 1-2 dB), but substantially reduces the power output requirements for each power amplifier associated with each antenna. The advantages of equal-gain composite beamforming are further described in the aforementioned co-pending application entitled "System and Method for Antenna Diversity Using Equal Gain Joint Maximal Ratio Combining." The initial transmit filter sub-vectors used by the first communication device in step 410 can optionally be equal gain normalized, as indicated in FIG. 4 with the $(N)^{½}$ factor.

[0035] In step 420, the first communication device receives the signal transmitted by the second communication device using the transmit sub-vectors $w^{j}_{T,D2}$ and estimates a vector corresponding to the product $W_{R,D1,0}e_{0}$ to obtain

the initial receive filter vector $w_{R,D1,0}$. At the next iteration in step 430, the first communication device performs a process similar to the one performed by the second communication device in step 420, to compute the principal eigenvector $u_{T,D1,1}$ and generate therefrom updated transmit filter sub-vectors for each antenna of the first communication device using either the equal gain computation or non-equal gain relationship.

[0036] Steps 440 and 450 show that this process repeats and the transmit filter sub-vectors at the first and second communication devices converge to values that optimize the received SNR at each of them. The transmit filter sub-vectors computed at each iteration are stored. Even though the transmit filter sub-vectors will ultimately converge after several iterations, they can be continuously updated with each transmission between those communication devices beyond convergence. In addition, it may also be desirable to store the most recent or updated transmit filter sub-vectors in one communication device against and identifier of the particular destination communication device. In this way, when a subsequent communication session is initiated between those same communication devices, each device can retrieve the stored

transmit filter sub-vectors for use in transmitting signals to the other device.

[0037] Optimizing the transmit filters at the first and second communication device in this way significantly increases the range (i.e., distance) between the devices. This can be very advantageous in a wireless communication environments, such as short-range wireless applications. A wireless LAN is one example of a short-range wireless application.

[0038] The computations referred to in the description of the iterative process 400 may be performed by the discrete signal computation blocks 160 and 260 (using digital signal processing techniques), respectively, in communication devices 100 and 200. For example, when communication device 100 or 200 receives a signal from the other device, there is a channel estimator computation block that estimates the composite channel transmit filter response of the transmitting communication device in order to determine the receive super matrix W_R. There is a computation block that forms the receive vector w_R and from that vector builds the receive convolution matrix W^j_R for each antenna. There are also one or more computation blocks that compute super matrix W_R, the Hermitian of

the receive super matrix W_R, multiply it with the receive matrix W_R and compute the principle or principal eigenvector of the matrix product of that matrix multiplication. Computation blocks are also provided that normalize each sub-vector (divide by the norm of the principal eigenvectors and by the square-root of the number of antennas) for each antenna sub-vector. Moreover, the transmit antenna filters and receive antenna filters in each communication device may similarly be implemented by computational blocks.

[0039] FIGs. 5 to 7 show various performance metrics of the iterative scheme. FIG. 5 shows the loss in SNR of the iterative scheme of FIG. 4 relative to the case where the channel state is known at the transmitting device (hereinafter called the "ideal case"). The loss in SNR due to the iterative scheme is less than 2 dB for more than 90% of channel realizations.

[0040] FIG. 6 shows loss in SNR using the equal gain constraint in the ideal case relative to the non-equal gain ideal case. That is, both communication devices, when transmitting to the other device, constrain the power of the signal at each antenna to be equal. The loss in SNR for the equal gain case is less than 1 dB for more than 90% of channel

realizations.

[0041] FIG. 7 shows the loss in SNR using the equal gain constraint in the iterative scheme of FIG. 4. The loss in SNR using equal gain is less than 1 dB for more than 90% of channel realizations.

[0042] FIG. 8 shows a more complete exemplary block diagram of a communication device useful in accordance with the techniques described herein. The communication devices at both ends of the link , i.e., devices 100 and 200 may have any known suitable architecture to transmit, receive and process signals. An example of a communication device block diagram is shown in FIG. 8. The communication device comprises an RF section 310, a baseband section 320 and optionally a host 330. There are a plurality of antennas, e.g., four antennas 302, 304, 306, 308 coupled to the RF section 310 that are used for transmission and reception. The RF section 310 has a transmitter (Tx) 312 that upconverts baseband signals for transmission, and a receiver (Rx) 314 that downconverts received RF signals for baseband processing. In the context of the composite beamforming techniques described herein, the Tx 312 upconverts and supplies separately weighted signals to corresponding ones of each of the plurality of antennas

via separate power amplifiers. Similarly, the Rx 314 down-converts and supplies received signals from each of the plurality of antennas to the baseband section 320. The baseband section 320 performs processing of baseband signals to recover the information from a received signal, and to convert information in preparation for transmission. The baseband section 320 may implement any of a variety of communication formats or standards, such as WLAN standards IEEE 802.11x, frequency hopping standards such as Bluetooth™, as well as other protocol standards, not necessarily used in a WLAN. In the case of frequency hopping systems, the antenna sub-vectors are computed and stored for each frequency in a frequency hopping sequence.

[0043] The intelligence to execute the computations for the composite beamforming techniques described herein may be implemented in a variety of ways. For example, a processor 322 in the baseband section 320 may execute instructions encoded on a processor readable memory 324 (RAM, ROM, EEPROM, etc.) that cause the processor 322 to perform the composite beamforming steps described herein. Alternatively, as suggested above, an application specific integrated circuit (ASIC) may be fabricated with the appro-

priate firmware e.g., field programmable gate arrays (FPGAs), configured to execute the computations described herein. This ASIC may be part of, or the entirety of, the baseband section 320. For example, the components shown in FIG. 1 as part of the communication devices may be implemented by FPGAs in the baseband section 320. Still another alternative is for the beamforming computations to be performed by a host processor 332 (in the host 330) by executing instructions stored in (or encoded on) a processor readable memory 334. The RF section 310 may be embodied by one integrated circuit, and the baseband section 320 may be embodied by another integrated circuit. The communication device on each end of the communication link need not have the same device architecture or implementation.

[0044] To summarize, a method is provided for communicating signals between a first communication device and a second communication device using radio frequency (RF) communication techniques. At the first communication device there are steps of generating a transmit filter vector for processing a signal to be transmitted from the first communication device to the second communication device, the transmit filter vector comprised of a plurality of

transmit filter sub-vectors defining one or more complex weights associated with a transmit tapped-delay line filter, each transmit filter sub-vector associated with a corresponding one of a plurality of antennas of the first communication device and having a length corresponding to the number taps of the associated transmit tapped-delay line filter; and applying the transmit filter vector to a signal to be transmitted from the first communication device to the second communication device.

[0045] At the second communication device there are steps of generating a receive filter matrix from a signal received by the one or more antennas of the second communication device from the first communication device, the receive filter matrix comprised of one or more sub-matrices each being a convolution matrix derived from a receive filter sub-vector, wherein each receive filter sub-vector defines one or more complex weights associated with a receive tapped-delay line filter for the one or more antennas of the second communication device; computing a principal eigenvector of a product of the receive filter matrix and a Hermitian of the receive filter matrix, the principal eigenvector comprised of one or more sub-vectors each having a length corresponding to a number of taps of a transmit

tapped-delay line filter associated with the one or more antennas of the second communication device; deriving from the one or more sub-vectors of the principal eigen-vector one or more transmit filter sub-vectors that form a transmit filter vector, each transmit filter sub-vector corresponding to the one or more antennas of the second communication device and defining one or more complex weights associated with the transmit tapped-delay line filter for the one or more antennas of the second communication device; and applying the transmit filter vector at the second communication device to a signal to be transmitted from the second communication device to the first communication device. The transmit filter vector at either or both of the first and second communication devices may be normalized at each sub-vector so that the total power associated with a transmitted signal is divided equally among the plurality of antennas of the first communication device.

[0046] Similarly, a method is provided for radio communication between a first communication device and a second communication device, comprising steps of generating a transmit filter vector for processing a signal to be transmitted from the first communication device to the second

communication device, the transmit filter vector comprised of a plurality of transmit filter sub-vectors defining one or more complex weights associated with a transmit tapped-delay line filter, each transmit filter sub-vector associated with a corresponding one of a plurality of antennas of the first communication device and having a length corresponding to the number taps of the associated transmit tapped-delay line filter; applying the transmit filter vector to a signal to be transmitted from the first communication device to the second communication device; generating a receive filter matrix from a signal received by the plurality of antennas of the first communication device from the second communication device, the receive filter matrix comprised of a plurality of sub-matrices each being a convolution matrix derived from a receive filter sub-vector, wherein each receive filter sub-vector defines one or more complex weights associated with a receive tapped-delay line filter process for the each of the plurality of antennas of the first communication device; computing a principal eigenvector of a product of the receive filter matrix and a Hermitian of the receive filter matrix, the principal eigenvector comprised of a plurality of sub-vectors each having a length corresponding to the

number of taps of the transmit tapped-delay line filter process of the first communication device; and updating from the plurality of sub-vectors of the principal eigen-vector the plurality of transmit filter sub-vectors. This method may be implemented by instructions encoded on a medium, such as a processor readable medium, or by instructions implemented by one or more arrays of field programmable gates.

[0047] Further still, a semiconductor device is provided comprising a plurality of field programmable gates configured to implement: a plurality of transmit tapped delay-line filters, each associated with a corresponding one of a plurality of antennas; a plurality of receive tapped delay-line filters, each associated with a corresponding one of the plurality of antennas; and one or more computation blocks that generate a transmit filter vector for processing a signal to be transmitted to another communication device, the transmit filter vector comprised of a plurality of transmit filter sub-vectors defining one or more complex weights associated with the transmit tapped-delay line filter, each transmit filter sub-vector associated with a corresponding one of the plurality of antennas and having a length corresponding to the number taps of the associ-

ated transmit tapped-delay line filter; apply the transmit filter vector to a signal to be transmitted from the other communication device; generate a receive filter matrix from a signal received by the plurality of antennas from the other communication device, the receive filter matrix comprised of a plurality of sub-matrices each being a convolution matrix derived from a receive filter sub-vector, wherein each receive filter sub-vector defines one or more complex weights associated with a receive tapped-delay line filter process for the each of the plurality of antennas; compute a principal eigenvector of a product of the receive filter matrix and a Hermitian of the receive filter matrix, the principal eigenvector comprised of a plurality of sub-vectors each having a length corresponding to the number of taps of the transmit tapped-delay line filter process; and update from the plurality of sub-vectors of the principal eigenvector the plurality of transmit filter sub-vectors. The semiconductor device may be, for example, an digital application specific integrated circuit implemented using field programmable gate arrays or digital logic implementations, such as CMOS digital logic.

[0048] The above description is intended by way of example only.